Proof of Concept and Experimental Design for Remote Laser Evaporative Molecular Absorption Spectroscopy Sensor System (R-LEMA)

A Senior Project
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Bachelor of Science

by

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Abstract

As the Earth's resources are diminishing, it has become clear that the human race needs to find alternative resources and replenish the Earth's natural reservoir. One way to do this is to consider interstellar objects. Interstellar objects, such as asteroids, offer mineral and other resources with great potential for mining.[1-5] Before considering mining a rocky body, it is imperative to first know the complete composition of an object. Using the method of traveling to the objects, drilling into them, and bringing back samples is impractical, inefficient, and expensive. This method is also limiting, as only certain target areas of the body can be brought back and analyzed. A method to collect composition data remotely becomes almost necessary. One method to do so is to use remote laser evaporative molecular absorption spectroscopy sensor system, or R-LEMA.[6,7] R-LEMA uses a high-power laser source to heat up and evaporate a rocky body. The molten material provides an infrared blackbody source to backlight evaporated material. An absorption spectrum can be taken for compositional analysis. The laser can be locked on to one target location on a body, and probe deep into the body, providing data on the entirety of the object. This paper will describe an experimental set up for R-LEMA, compare R-LEMA to other methods with similar goals, and provide results from performed R-LEMA experiments. R-LEMA will be validated, and future development of the system will be described.

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Background

Spectroscopy

In order to understand the R-LEMA system, it is first important to understand what spectroscopy is, and what is meant by absorption spectroscopy. Spectroscopy is the study of the interaction between matter and electromagnetic radiation, more commonly referred to as light. There are many types of spectroscopy available to researchers today. The goals of this project are only concerned with atomic and molecular spectra. As a result, two primary types of spectroscopy are available to use. They are atomic emission spectroscopy and atomic absorption spectroscopy.

Emission spectroscopy is more commonly used in visible and ultraviolet wavelengths. Emission spectroscopy involves providing energy to a source material. This energy excites electrons on an atom or molecular structure in a target material to a higher energy state. Electrons tend to occupy the lowest energy state available to them. When excited to a higher energy state, the electron wants to return back to a lower energy state. In order to do so, the electron must release some energy. The energy is released in the form of a photon, which carries electromagnetic information. This photon is referred to as the characteristic photon. The photons released from this process are collected by a spectrometer and processed into a spectrum. The spectrum will show several lines or peaks indicating the wavelengths of the emitted photons.[8] This emission spectrum can be analyzed in order to determine which atomic and molecular structures are present in a sample as it is known which characteristic photons specific atoms emit. A typical atomic discharge tube works on the same principles, as gaseous elements are provided energy and appear to glow a characteristic color. This glow comes from released characteristic photons, as atoms are excited, deexcited, and excited again. An emission spectrum of a discharge tube will show very few emission lines specific to the atom in the tube.

Absorption spectroscopy typically operates at lower energy or infrared wavelengths so as not to excite electrons and prompt the release of photons. Rather than providing energy to a source, absorption spectroscopy requires a source to be backlit by a low energy light source. A target source much have the ability to let some light source through so that photons can be collected by a spectrometer.[9] For example, a target source can be transparent or can be in a gaseous state. As the light source passes through a material, electrons in atoms and molecular structures absorb low energy photons. The photon wavelengths absorbed are specific to each atomic structure. As a result, some wavelengths of the initial light source will be absent after passing through a source material. This light can be received and processed in a spectrometer. The spectrum indicates which wavelengths are absorbed by displaying absorption lines. The spectrum provides insight to a material's composition.

R-LEMA

R-LEMA, or Remote Laser Evaporative Molecular Absorption Spectroscopy, describes a sensory concept which can be used to analyze the composition of an object in outer space. The R-LEMA system is ultimately to be put into a CubeSat satellite. This will allow for a sample to be remotely analyzing in space using the processes described in this paper.[10]

The system uses the basic principles of absorption spectroscopy. However, the system has to create its own low energy light source to backlight a sample. It does this by using a laser of power about 10 MW/m^2 to provide sufficient energy to heat up, melt, and evaporate a rock source.[10] The spot affected by the laser will rapidly increase in temperature to about 2500K, allowing for evaporation. Yet, the laser does not provide enough energy to disassociate molecules or to cause ionization once molecules are in a gaseous plume state. Melted material in liquid form on the rock is very hot and releases thermal radiation. This thermal radiation is essentially a blackbody source. Now, thermal radiation from the rock acts as a backlight in the infrared, while evaporated material lying just at the surface of the rock acts as a source to be analyzed.[10]

As the thermal radiation passes through the plume of material, some wavelengths of the blackbody light will be absorbed. Absorption is dependent on the identity of the materials in the plume.[9] Each molecule and atom absorb a different wavelength of the light source, just as in standard absorption spectroscopy. Once the signal passes through the plume, only wavelengths that are not absorbed are present. This signal is be directed into a spectrometer, in this case a Fourier Transform Infrared (FT-IR) spectrometer, for analysis. An absorption spectrum will be generated, with absorption lines coinciding with absorbed wavelengths. Comparative analysis is then performed against absorption lines of known compounds and substances.

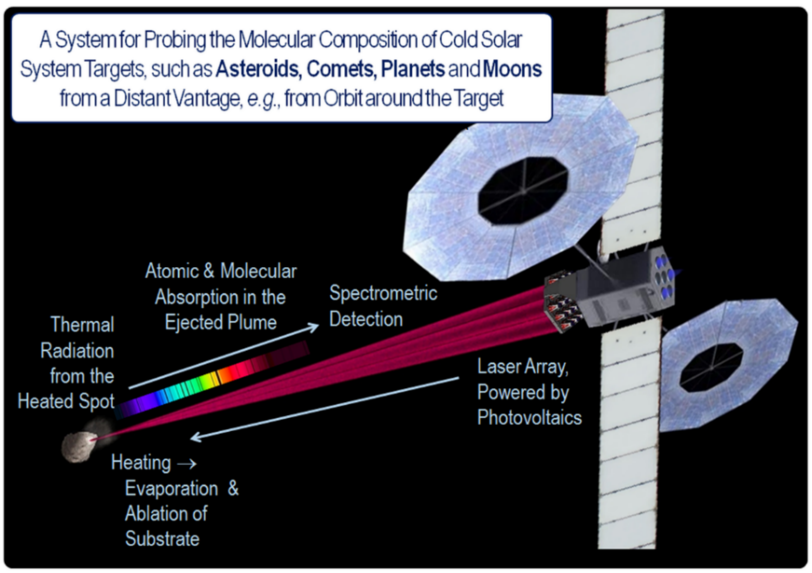

Figure 1 *A visual representation of the theorized R-LEMA system.*[10]

Other Methods

Some complementary methods achieving the same goal as R-LEMA are currently in existence. These include the Laser Induced Breakdown Spectroscopy (LIBS) and Laser Induced Thermal Emission (LITE) methods.

LIBS utilizes atomic emission spectroscopy rather than absorption spectroscopy. A high energy laser pulse of flux about 10 TW/m^2 is directed at a target and provides enough energy to create a plasma plume of excited atoms. These excited atoms reach temperatures of up to 30,000K. As the atoms de-excite, they release characteristic photons generally in optical and ultraviolent wavelengths. These photons, travelling with discrete wavelengths, can be recorded by a spectrometer. Emission lines on an emission spectrum give insight to what materials and elements are present in the sample.[11]

LITE uses atomic emission spectroscopy as well as LIBS. LITE uses a low energy laser to heat target materials to temperatures higher than the surrounding environment. The materials are kept in a solid phase. An infrared spectrometer analyzes a source by employing an infrared imaging system. The infrared imaging system focuses infrared light onto the infrared spectrometer. Materials in the target source emit optical wavelengths originating from vibrational and rotational movement of molecules. LITE is typically used for molecular compositional analysis as it generates a low signal of optical wavelengths.[12]

Benefits of R-LEMA

While both the LIBS and LITE methods have proven successful, there are limitations faced by both that R-LEMA does not share.[10]

LIBS is primarily limited by inherently faint atomic emission signals. In order for a plasma to be generated on a distant target, the laser must provide about 10 TW/M^2. This in turn limits the probing distance of the LIBS system from a target source. The light to be analyzed by the spectrometer must also be of sufficient intensity. This limits the system further as the spectrometer must be close enough to the source to analyze the characteristic photons. Since R-LEMA uses a laser operating at a lower flux of 10 MW/m^2, the system can operate at further distances from the target source. R-LEMA can view an object at much further distances than its competitor LIBS.[10]

LITE, since also analyzing in the infrared, is expected to yield very similar results as R-LEMA. However, LITE operates in the solid state, while R-LEMA operates in the gas phase. In a gas phase, some unique features may be present that are missing when a sample is in a solid phase. These features include some rotational absorption lines. These lines cannot be present when a sample is in solid phase as molecules are bound together. This is seen in Raman scattering, for example, which is thought to result from different physical processes in solid phase and gas phase. R-LEMA spectroscopy provides more information than LITE spectroscopy.[10]

In both cases, significant damage is done to the rocky body in question. However, as R-LEMA only probes at one single target location, minimal damage is done to the object. This allows for an object to be used for resource consumption.

Apparatus

The goal of the experimental design is to successfully focus a blackbody thermal radiation signal into an FT-IR spectrometer, in order to identify what wavelengths of light are present. This thermal source will eventually evolve into a glowing asteroid simulant heated by a directed laser in future experimental set ups.

The preliminary experiment simulates a black body source, and collects an absorption spectrum of the provided source.[10] Specifically, the source will emit electromagnetic radiation, travel through a source material, be partially absorbed, and finally travel through the optics to be analyzed by an FT-IR spectrometer. Several subsections of the apparatus must be arranged so that they can work together to meet the goals of the experiment. It is important to first understand how each component works on its own before the entire experimental set up can be understood.

Optics

The largest part of the design is the optical set up. The light from the blackbody source cannot be analyzed if it is not first focused into the spectrometer. Figure 2 shows the optical table and the components as they are laid out in the laboratory. In the preliminary experiments, a HeNe laser light source is placed on one end of the table taking the place of the blackbody source. The light source is shone onto an off-axis parabolic mirror, or an OAP mirror. This first mirror acts as the primary mirror, with dimensions Ø50.8 mm by 646 mm. The primary is rotated 15^{o} from the axis. From the primary, the light is reflected to a flat mirror, with diameter 50.8 mm. The flat is rotated 7.5^{o} from the primary, causing some marginal rays to be lost. The flat mirror reflects the light to another OAP, referred to as the secondary mirror. The secondary mirror has dimensions Ø50.8 mm by 152.4 mm and is rotated 90^{o} from the axis. The secondary then reflects the light to a spectrometer. All mirrors used are coated in gold, as gold is highly reflective at infrared wavelengths. Since the final experiment will integrate a true IR blackbody, god mirrors are a fitting choice. This optical set up optimizes the focus of the light source at the spectrometer input.[10]

In front of the secondary, a smaller OAP rotated 90^{o} with dimensions Ø25.4 mm by 50.8 mm directs light into a photodiode. This mirror and the photodiode are essential pieces in a feedback loop discussed in the advanced experiment section of this paper.

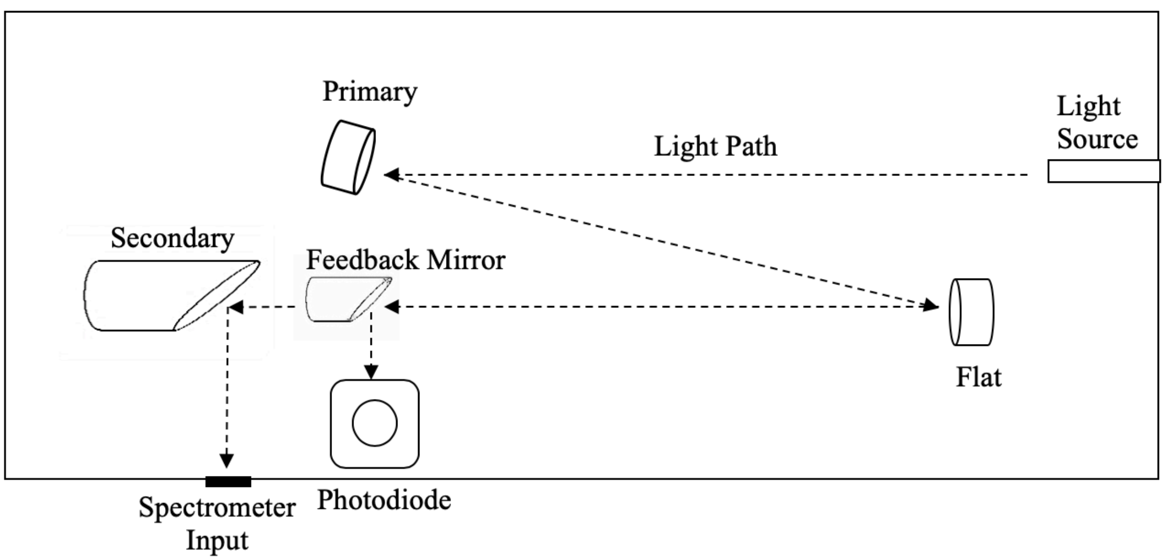

Figure 2 *The optimized optical set up for the R-LEMA experiment. Note: this figure is not to scale.*

Light Source

In preliminary R-LEMA experiments, a HeNe is was used. The laser serves as a guide for optical alignment. Power into the spectrometer and photodiode is monitored, and the spectrometer is tested. A spectrum of the HeNe laser is taken to ensure the experiment works as expected.

Once the alignment is perfected, several thermal sources are tested. First, a 100 W, 12 V incandescent bulb is used. The bulb light is similar to a blackbody in behavior. The light from the bulb is focused into the spectrometer, providing a full-scale signal.

After confirming the system works with a thermal source, the light bulb is replaced with a glowing platinum filament. This platinum filament better simulates a thermal blackbody source emitted from a glowing spot on an asteroid or other rocky body. To achieve the glow, current is run through the filament. The wire starts to glow at 30 A and 2 V, resulting in 60W of power. While this does not achieve as much power as the light bulb, the wire source spectrum is not contaminated by the bulb material, presumably silica. The filament source is focused onto the spectrometer, providing approximately 2/3 of the full-scale signal. The filament is to be replaced with glowing asteroid simulant heated by a high power (10MW/m^2) laser. This laser-simulant system has been developed separately from preliminary optical experiments and is to be integrated into the optics board in place of the platinum wire in future iterations.

Spectrometer

In order to process the light signal, a spectrometer is necessary. In this lab, the Bruker Vertex 80 FT-IR spectrometer was chosen. Specifically, the Bruker Vertex 80 is analyzing absorption spectra of a provided source. The spectrometer can analyze a sample in two modes: an internal sample and an external sample.[13]

The internal sample mode is very easy to use. A sample is loaded into the spectrometer in the internal test sample compartment at room temperature. The environment surrounding the spectrometer must also be very dry. The spectrometer is provided purged gas to keep the internal sample environment as pure as possible. The purged gas also provides air for the air bearings in which the internal optics of the spectrometer lie. Any material can be loaded into the test compartment. A built-in light source shines through the material. Wavelengths of light absorbed by the material do not pass through to the detector. The spectrometer then analyzes the absorption spectra for the test sample material.[13] The internal sample is primarily used to confirm the correctness of external sources in this laboratory.

The external sample mode is slightly more involved to use. A sample lies outside of the spectrometer, as shown in figure 3. The environment, just like with an internal sample, must be very dry with low humidity. The detector that captures external light cannot operate in room temperature conditions. The detector must be cooled to very low temperatures with liquid nitrogen, which can be put directly into the spectrometer through the liquid nitrogen port. The light to be analyzed must be precisely focused onto the center of the input. Within the spectrometer beyond the input screen lies another optical set up that guides the light to the detector. These optical components lie on air bearings to allow for very small precise movements and measurements.[13] This means extensive optical alignment must be performed on the optics table to guide the light to the internal optics in the spectrometer.

The Bruker Vertex 80 spectrometer also allows for correction of a fluctuating light source. With a glowing asteroid simulant, power given off is varying unpredictably, as further described in advanced experiment. This specific spectrometer can read a power fluctuation signal from a photodiode sent through the BNC ports, and correct noise in a spectrum according to power fluctuations. In this set up, the photodiode sends power readings to the BNC ports.[13] This is essential for further development of R-LEMA experiments.

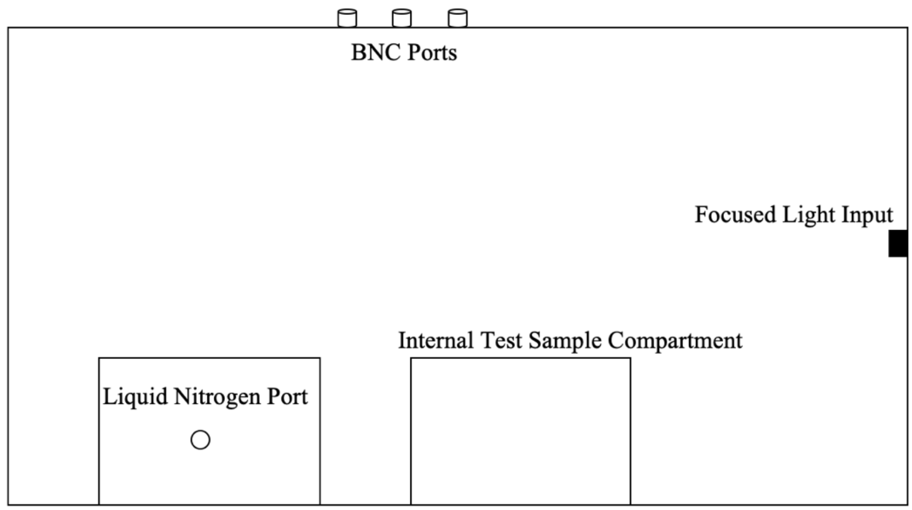

Figure 3 *A simplified visual of the Bruker Vertex 80 FT-IR spectrometer.*

Electronics

This experimental apparatus requires some electrical components as well. Specifically, an oscilloscope, preamplifier, power supply, and function generator are all required.

An oscilloscope can be used to monitor power output of the light source. Using an oscilloscope, any variation in a power signal can be easily monitored in real time. The light source is focused into the infrared photodiode. The signal is sent from the photodiode to the oscilloscope using BNC connections. Monitoring this signal becomes necessary when a non-constant light source is present, as described in the advanced experiments section.

While the oscilloscope can monitor changes in a power signal, changes are often so small that they can be easily missed. More importantly, the spectrometer requires a ±10 V external signal in order to normalize the interferogram intensity at each mirror position when a feedback loop is introduced. To solve this problem, a low-noise wideband preamplifier can be used to boost the output to a viable level for both monitoring and for use by the spectrometer. The preamplifier requires an input from a low noise power supply and an input from the infrared photodiode. The output can then be monitored on the oscilloscope.

In order to check the circuitry, a function generator is used. A constant square wave is constructed and fed into the oscilloscope. Any changes in the desired photodiode signal are much more evident when compared in real time to the constant square wave. The square wave signal can also be fed into the amplifier to ensure the correct gain is achieved.

Total Apparatus

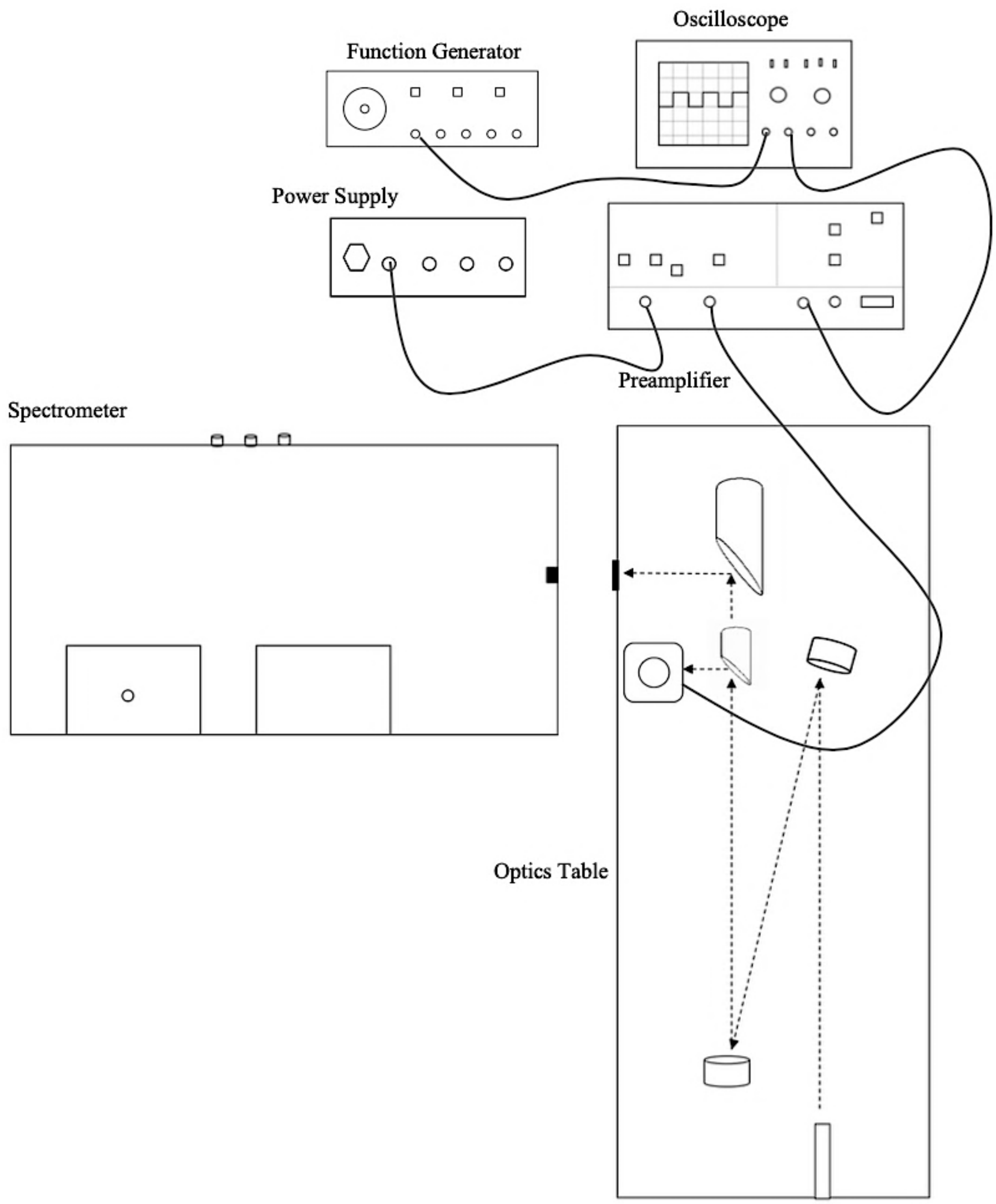

Figure 4 *The total apparatus is shown.*

Experiment

Preliminary

Before experimentation can begin, a proper lab environment needs to be created. Since the spectrometer needs a low humidity environment to operate, certain precautions are taken. A dehumidifier is run at all times in the lab room. The humidity and temperature are monitored to ensure the environment does not become too moist. As the spectrometer's optics lie on air bearings, pressurized air must be provided to the spectrometer so that internal pressure requirements are met. A purge gas generator provides air at all times to the spectrometer so that the optics sit on their bearings and are not damaged.

The optics board described in the optics section can be assembled. The first step in this experimental procedure is to gain an understanding of what results to expect. The internal port of the spectrometer is used to collect a small library of samples for later comparison to the samples collected using the external port. A latex sample will be highlighted for the purposes of this paper. A background spectrum of the internal cavity is taken. A piece of latex glove is loaded into the sample compartment. The spectrometer takes a sample spectrum of the latex glove. The Bruker software subtracts the background from the sample spectrum. Background includes any residual moisture in the air within the port.

After the external port detector is cooled using liquid nitrogen, a light source must be introduced independent of the spectrometer. In early versions of the experiment, a 100W incandescent light bulb is used. A background spectrum is taken and again will be subtracted from the sample spectrum by the Bruker software. A test sample of choice is placed in front of the light source. All other lights in the lab room are shut off to reduce ambient light polluting the spectrum. Again, a latex sample will be used in this discussion. The optical set up described in the optics section of this paper guides the light of interest to the spectrometer. The light source of choice passes through a sample, in this case latex, and is focused to the spectrometer. A spectrum is then taken and compared to the spectrum achieved using the internal port. In this experiment, the internal and external port samples were very close matches.

Advanced

Once the proof of concept is established, several advancements to the experiment can be made. These advancements aim to create an outer-space-like environment.

Outer-space is a vacuum environment. Hence, a vacuum chamber is required to remove all air and other gaseous particles from the environment. A unique chamber can be designed to encase the entirety of the optical table and input screen of the spectrometer. This ensures that the only wavelengths of light absorbed are due to the test material. This is as true to how an R-LEMA system would act in space.

A light source in the final product will not be glowing at constant intensity. There will be random variations in the flux of the light source. This is in part due to different materials melting, glowing, and evaporating at different temperatures. The laser is ideally locked onto one target location. As the laser probes deeper into an object, it encounters different materials. As materials heat up and glow, this causes a flickering effect of the hot spot on the sample. This can be reproduced in lab. First, in order to achieve a simple glow and ensure the intensity is great enough to be read by the spectrometer, a glowing platinum filament is used. As described in the light source section of this paper, the platinum wire glows at lower energy wavelengths when exposed to current and can be read by the spectrometer. This is closer to infrared radiation, which will be emitted by a rocky substance. However, the platinum filament glows with constant intensity, and does not fully simulate a true rocky substance in space. A high-power laser of 10 MW/m^2 can be targeted at an asteroid simulant provided by NASA. The simulant glows and fluctuates the way a rocky substance in space is expected to. This laser-simulant system is functioning, however has not yet been integrated onto the optics board. Figure five below shows this flickering light source.

A fluctuating source introduces a new problem: noise in the spectrum. The power changes create noise in the signal that may result in false lines appearing or hiding other absorption lines. In order to solve this, a feedback loop can be introduced. The feedback mirror provides the light of interest to a photodiode. The photodiode takes real-time measurements of power from the light source. The fluctuating power signal from the photodiode is sent to a pre-amplifier. The signal from the photodiode is not strong enough alone to provide a basis for correction to the spectrometer. Thus, the amplifier brings the signal up to ±10V. The signal is then fed from the amplifier to the BNC port of the spectrometer. The detection setting on the spectrometer is set to specify to account for the fluctuating external source, and a feedback loop is successfully introduced. Figure six shows the physical feedback loop integrated into the optics board.

Figure 5 *The flickering light source when a high-power laser is directed at a small rocky substance*

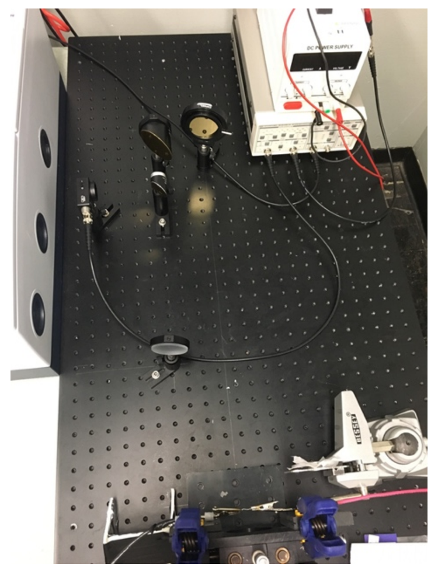

Figure 6 *The feedback loop integrated into the optics board*

Results

In preliminary experiments where a latex glove is chosen, spectra are successfully attained. The spectra are compared against the NIST database, in which spectra of several known compounds are stored.[14] The results produced in this experiment are consistent with those spectra in the NIST data base.[14] Figure seven shows the background spectrum taken in the internal port against the external port when only an incandescent light bulb is present. The background is subtracted from any spectra taken immediately after using the incandescent bulb as a light source. Major absorption lines, such as carbon dioxide and water in the lab environment, are easily identifiable. Figure eight shows the spectra taken of the latex glove sample backlit by an incandescent light bulb, both in the external and internal ports. Given the similarities with negligible differences in background, it can be determined the experiment is effective.

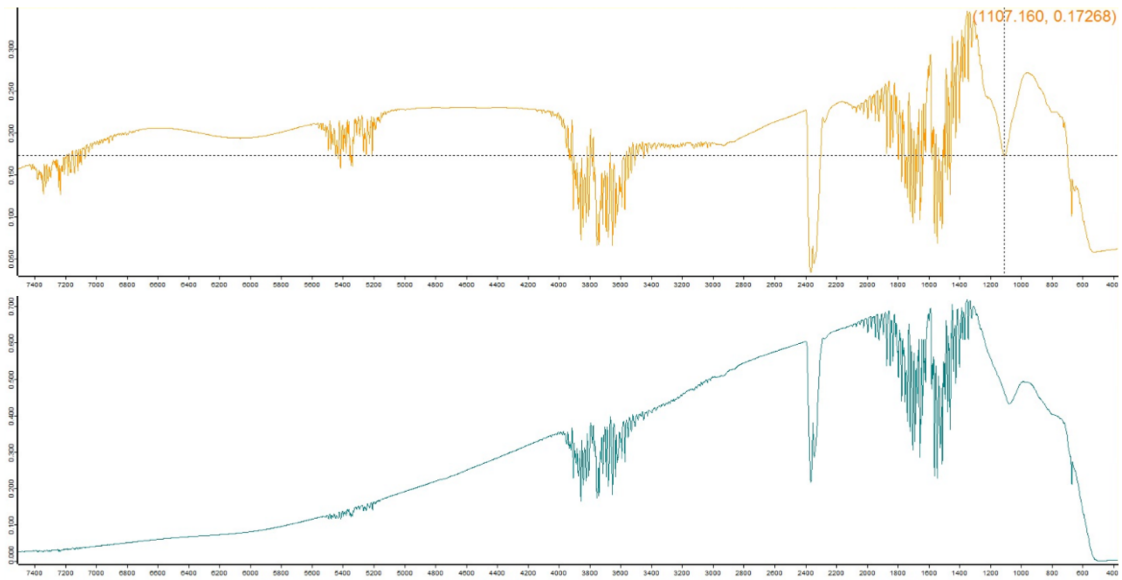

Figure 7 *Top: The background reading when an incandescent light bulb is present using the external port. Bottom: The background reading when an incandescent light bulb is present using the internal port.*

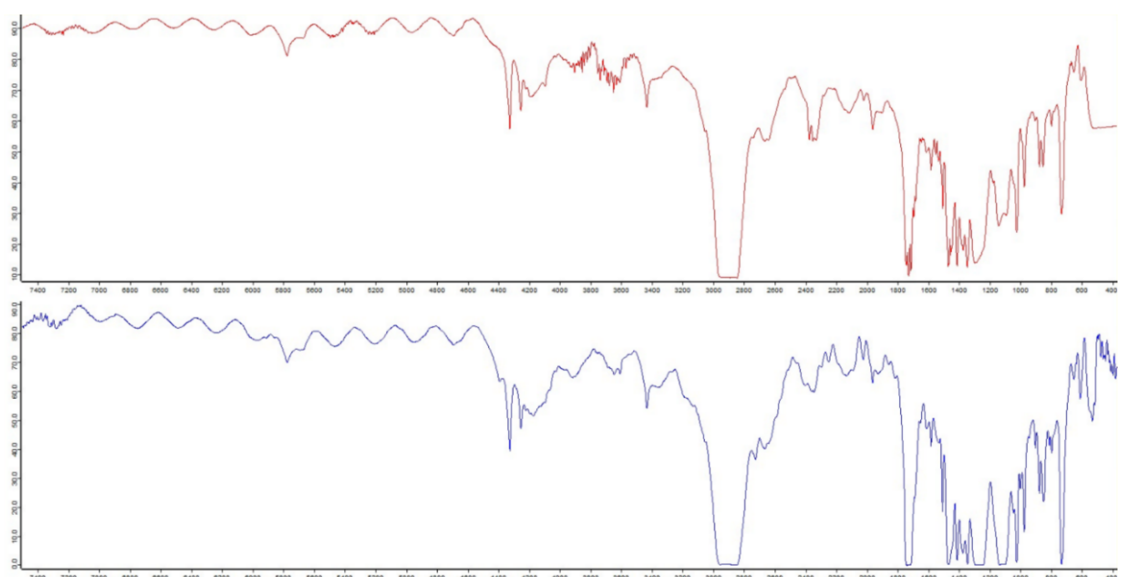

Figure 8 *Top: The spectrum of the latex glove backlit by an incandescent light bulb taken using the external port. Bottom: The spectrum of the latex glove backlit by an incandescent light bulb taken in the internal port.*

Future Developments

Since the preliminary experiments demonstrate compositional analysis via absorption spectroscopy is possible, several advancements are ready to be made.

With a feedback loop ready for use, a high-power laser can easily be integrated into the apparatus and mounted onto the optics board. The target source can be easily replaced with a rocky substance or an asteroid simulant. For this experiment, NASA has provided a replicated asteroid derived from their own research. The rocky simulant substance, when heated by a high-power laser, will fluctuate. This rocky substance will be used as both the test subject and the light source, just as theorized. Integrating the high-power laser and rocky substance is the next step towards launching this system into space.

A separate system with a high-power laser and rocky substance has been developed and tested in the lab. It can be implemented into the experiment previously described with ease.

Much work still needs to be done in order to condense the relatively large apparatus down to a size that will fit into a CubeSat satellite. A design of a CubeSat satellite needs to be developed which can accommodate such a system. These problems are outside of the scope of this paper.

Conclusion

R-LEMA allows for advancements in compositional analysis which competing methods cannot offer. Preliminary R-LEMA experiments have been proven to work. Future advancements can be made to show R-LEMA is a viable option for probing interstellar objects. Despite this, current laboratory experiments meet theorized expectations.

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